Top quark pair production measurements using the ATLAS detector at the LHC

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QCD 15

18th HIGH-ENERGY PHYSICS
INTERNATIONAL CONFERENCE
IN QUANTUM CHROMODYNAMICS (QCD)

Outline

- Inclusive cross section
- Differential cross section measurements
- Production in association with gauge bosons

The interest of the Top Quark

- Decay before hadronization -> access to bare quark
- The heaviest known fundamental particle (173.34 ± 0.76 GeV)
 - ⇒ special role in the electroweak Symmetry Breaking
- Sector to search for new physics
 - ⇒ additional $t\bar{t}$ production modes
 - ⇒ additional $t\bar{t}$ decay channels
 - ⇒ background for many searches
- Tests/Information for QCD :
 - ⇒ heavy quarks production calculation
 - ⇒ test and tune MC models
 - ⇒ PDF - ISR/FSR Modeling

$t\bar{t}$ production and decay

- Top pair production at the LHC through gg (>84%) and qq

Theory QCD precision
NNLO + NNLL soft gluon
resummation :

$$\Rightarrow \sigma_{(pp \rightarrow t\bar{t})} (7 \text{ TeV}) = 177_{-11}^{+10} \text{ pb}$$

$$\Rightarrow \sigma_{(pp \rightarrow t\bar{t})} (8 \text{ TeV}) = 253_{-15}^{+13} \text{ pb}$$

$$\Rightarrow \sigma_{(pp \rightarrow t\bar{t})} (13 \text{ TeV}) = 832_{-46}^{+40} \text{ pb}$$

(at $m_{\text{top}}=172.5 \text{ GeV}$)

[Czakon, Mitov, Fiedler, PRL 110 \(2013\) 252004](#)

- $t \rightarrow Wb$ ($\sim 100\%$) ;

Final state
depends on the
2 W decays

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Top Pair Branching Fractions

Inclusive $t\bar{t}$ cross section in the dilepton channel ($e\mu$) at 7 and 8 TeV

[Eur.Phys.J. C74 \(2014\) 3109](#)

ATLAS Data at 7 TeV (2011) : 4.6 fb⁻¹
8 TeV (2012) : 20.3 fb⁻¹

- 1 e + 1μ + 1 or 2 b-tagged jets
- Measure simultaneously $\sigma(t\bar{t})$ and b-jet efficiency to minimize systematics
- Extract also m_{top}^{pole} ($172.9^{+2.5}_{-2.6}$ GeV) and sets limits on direct stop pair production: exclusion of $m_{top} < M_{stop} < 177$ GeV at 95% CL
- Main syst : signal modeling

$\sigma(t\bar{t}) = 182.9 \pm 3.1(\text{stat}) \pm 4.2(\text{syst}) \pm 3.6(\text{lumi}) \pm 3.3(\text{beam})$ pb (7 TeV)	4%
$\sigma(t\bar{t}) = 242.4 \pm 1.7(\text{stat}) \pm 5.5(\text{syst}) \pm 7.5(\text{lumi}) \pm 4.2(\text{beam})$ pb (8 TeV)	4%

⇒ Results consistent with NLO+NNLL calculations : $\left. \begin{array}{l} 177 \text{ (7 TeV)} \\ 253 \text{ (8 TeV)} \end{array} \right\} 6\%$

Inclusive $t\bar{t}$ cross section in the lepton+jets channel at 8 TeV

[arXiv:1504.04251](https://arxiv.org/abs/1504.04251) - Submitted to JHEP

- 1 e or 1 μ + ≥ 3 jets (1b-tag)
+ E_T^{Miss} and M_T^W
- Use a likelihood discriminant variable (LHD) built from lepton η and transformed aplanarity A'
 $LHD = \mathcal{L}^s / (\mathcal{L}^s + \mathcal{L}^{bkg})$
- Fit of template in binned LHD to data
- Syst dominated by MC modeling (including PDF, ISR/FSR)

ATLAS Data at 8 TeV (2012) : 20.3 fb $^{-1}$

$$\sigma(t\bar{t}) = 260 \pm 1 \text{ (stat)} \cdot {}^{+20}_{-21} \text{ (syst)} \pm 8 \text{ (lumi)} \pm 4 \text{ (beam)} \text{ pb (8 TeV)}$$

(rel. error of 8%)

Inclusive $t\bar{t}$ cross section - Summary

- Very precise QCD prediction to NNLO with NNLL corrections available since 2013
- All measurements are limited by systematics
- Best results from dilepton side
- All measurements agree with predictions

Differential cross section

- Differential cross sections as a function of top or top pair variables:
 - ⇒ $P_T(t)$, $P_T(tt)$, $m(tt)$, $y(tt)$
- Measurements in both fiducial (inside acceptance) and full phase space
- Probe perturbative QCD, test and tune MC models with data
- Top quark full kinematic reconstruction necessary and background subtraction
- Unfolding techniques used (correcting bin to bin migration):
 - ⇒ Account for acceptance and detector effects (resolution, efficiency, etc.)
 - ⇒ Correct observed distributions to **parton-level** (generated quarks) or **particle-level** (stable hadrons after fragmentation, parton shower ...)
- Comparison with generators, PDF sets, calculations ...

Differential cross section (ℓ +jets): from reco to parton-level

[Phys. Rev. D 90, 072004](#)

- unfolded to top parton in full phase space
- Comparison with various MC generator with NLO-QCD and NLO+NNLL calculations
- Comparison with NLO predictions (MCFM) for different PDF sets
- Main syst : JES, JER, I/FSR, PS, MC modeling

- LO and NLO MCs generally **harder than data**, increasing with $P_T(t)$
- Data is **softer** than both **QCD NLO** and **NLO+NNLL calculations** in high $P_T(t)$ and high $m(t\bar{t})$
- **HERAPDF1.5** describes data best at high $P_T(t)$ and $m(t\bar{t})$

Differential cross section (ℓ +jets): from reco to particle-level

[arXiv:1502.05923](https://arxiv.org/abs/1502.05923): Submitted

- Reconstruction of pseudo-top at detector level and particle level
⇒ less dependence on fragmentation, parton shower, hadronization, PDFs,... (often non-perturbative)
- Fiducial measurement (less model-dependant)
- Main systematics: b-tagging, jet energy, ISR/FSR, parton shower
- Similar results as at parton level but with lower uncertainties

Differential cross section (ℓ +jets):boosted top at 8 TeV

[ATLAS-CONF-2014-057](#)

- First boosted top pair differential cross section measurement
 - ⇒ Hadronic top reconstructed as a large jet (anti-kt with $R=1.0$) of $P_T > 300$ GeV with sub-structure cuts (2 hard sub-jets)
 - ⇒ Cross section as function of this boosted $P_T(t)$
 - ⇒ Unfolding to particle-level (in fiducial region) then to parton-level (in full phase-space)
 - ⇒ Main syst : JES for large R jet, signal modeling at parton level
- Same results as seen at low $P_T(t)$ in 7 TeV data:
 - ⇒ LO and NLO MCs harder than data increasing with P_T
 - ⇒ For PDF HERAPDF best describes data

Differential cross section for $t\bar{t}$ +jets

[JHEP01\(2015\)020](#)

- $\sigma(t\bar{t}+\text{jets})$ as function of jet multiplicity or jets P_T (several P_T thresholds) at particle-level
- Sensitivity to parton shower modeling at high jet multiplicity
- Main systematics: from background modelling (at lower jet multiplicities) to jet energy scale (at higher jet multiplicities).
- POWHEG+PYTHIA with limited hard radiations (hdamp): best Data description
- MC@NLO+HERWIG: predicts too few events at high jet multiplicities

$t\bar{t}$ +boson (γ) measurement

[Phys. Rev. D 91, 072007 \(2015\)](#)

- ℓ +jets channel ; tight photon
- Fiducial measurement
- Main syst : object IDs (jets, photon, btag) and signal modeling

- Observation at 5.3σ
 - $\sigma_{t\bar{t}\gamma}^{\text{fid}} \times \text{BR} = 63 \pm 8 \text{ (stat)} ^{+17}_{-13} \text{ (syst)} \pm 1 \text{ (lumi)} \text{ fb}$
- ⇒ good agreement with the LO calculation normalized to the NLO prediction : $48 \pm 10 \text{ fb}$

$t\bar{t}$ +boson (W, Z) measurement

[ATLAS-CONF-2014-038](#)

- dilepton (same sign and opposite sign)+trilepton
- Background reduction by cuts on b-tags and jet multiplicity
- Dominated by statistics
- Evidence of $t\bar{t}Z$ and $t\bar{t}W$: 3.1σ (each)
- Cross sections consistent with NLO QCD calculations

Conclusion

- Top quark pair production measurements in ATLAS have reached good precision level. Theoretical calculations challenged by precision of experimental data (at hadronic collider)
- Differential measurements (fiducial/inclusive) of $t\bar{t}$ production in top P_T and other kinematics provide constraints to improve MC modeling and parameter tuning in $t\bar{t}$ production.
- Observation/evidence of associated production with gauge bosons. Cross section consistent with the SM.
- ATLAS is ready for more top physics in the TeV regime !

The ATLAS top program is very rich (see also next talk)

For more information and results

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults>

Extra Slides

Inclusive $t\bar{t}$ cross section in the dilepton channel ($e\mu$) at 7 and 8 TeV

Table 4. Summary of the relative statistical, systematic and total uncertainties on the measurements of the $t\bar{t}$ production cross-section $\sigma_{t\bar{t}}$ at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.

Uncertainty $\sqrt{s}$	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	
	7 TeV	8 TeV
Data statistics	1.69	0.71
$t\bar{t}$ modelling and QCD scale	1.46	1.26
Parton distribution functions	1.04	1.13
Background modelling	0.83	0.83
Lepton efficiencies	0.87	0.88
Jets and b -tagging	0.58	0.82
Misidentified leptons	0.41	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	2.27	2.26
Integrated luminosity	1.98	3.10
LHC beam energy	1.79	1.72
Total uncertainty	3.89	4.27

As shown in Tables [3](#) and [4](#), the largest systematic uncertainties on $\sigma_{t\bar{t}}$ come from $t\bar{t}$ modelling and PDFs, and knowledge of the integrated luminosities and LHC beam energy.

Correlation between $\sigma(t\bar{t})$ and m_{top}^{pole}

Combination 7 and 8 TeV :

$$m_{top}^{pole} = 172.9^{+2.5}_{-2.6} \text{ GeV}$$

Inclusive tt cross section in the lepton+jets channel at 8 TeV

Table 2: Summary of the systematic uncertainties in the measurements of the $t\bar{t}$ production cross-section (%). The bottom part of the table lists systematic uncertainties for the fiducial $t\bar{t}$ production cross-section for the cases where they are different from those for the inclusive one.

Uncertainty on inclusive $\sigma_{t\bar{t}}$	e +jets	μ +jets	ℓ +jets
Lepton reconstruction	+2.7 -2.6	+2.1 -1.9	+1.7 -1.6
Jet reconstruction / E_T^{miss}	+3.3 -3.9	+2.6 -3.2	+2.8 -3.4
b -tagging	+2.1 -1.9	+2.2 -1.9	+2.1 -1.9
Backgrounds	+2.8 -3.0	+1.8 -2.1	+1.7 -2.1
Monte Carlo generator	-0.7 +0.7	+0.1 -0.1	-0.3 +0.3
Parton shower/fragmentation	+2.0 -2.0	+2.6 -2.6	+2.3 -2.3
Initial-/final-state radiation	-4.1 +4.1	-1.8 +1.8	-3.0 +3.0
Parton distribution functions	+6.2 -6.0	+5.6 -5.9	+5.9 -5.9
Total	+9.4 -9.5	+7.9 -8.2	+8.2 -8.4
Uncertainty on fiducial $\sigma_{t\bar{t}}$	e +jets	μ +jets	ℓ +jets
Monte Carlo generator	+1.5 -1.5	+1.8 -1.8	+1.6 -1.6
Parton shower/fragmentation	-2.6 +2.6	-3.1 +3.1	-2.9 +2.9
Initial-/final-state radiation	+0.4 -0.4	+0.2 -0.2	+0.3 -0.3
Total	+9.1 -8.8	+8.0 -8.5	+7.9 -8.3

Transformed Aplanarity :
 $A' = \exp(-8A)$

Uncertainties between particle and parton level

In the boosted top analysis, comparison of uncertainties

From detector to particle

From detector to parton

Differential cross section for $t\bar{t}$ +jets

- The production of additional jets is sensitive to high-order perturbative QCD effect. The uncertainty associated is a source of uncertainties in other precision measurements.
- The cross section is also measured as function of each jet P_T

$t\bar{t} + \gamma$ measurement

Similar to ℓ +jets selection+1 tight photon (to suppress hadron decay like $\pi^0 \rightarrow \gamma\gamma$)
Cut on ΔR between lepton and jets.

Signal extraction with a template-based profile likelihood fit on the

$$P_{\text{Tiso}} = \sum_{\substack{\text{tracks in a} \\ \text{cone } \Delta R = 0.2 \\ \text{around the photon}}} P_T$$

Backgrounds: Misidentified jets or electrons as photons and prompt photons.

152 ± 31 signal events and
 199 ± 47 background events

Uncertainty source	Uncertainty [%]
Background template shapes	3.7
Signal template shapes	6.6
Signal modeling	8.4
Photon modeling	8.8
Lepton modeling	2.5
Jet modeling	16.6
b -tagging	8.2
E_T^{miss} modeling	0.9
Luminosity	1.8
Background contributions	7.7

$t\bar{t}$ +boson (W, Z) measurement

	Trilepton and same-sign dilepton			Opposite-sign dilepton	
Analysis strategy	comparable signal and background: cut and count			small signal in huge background multivariate techniques	
	$3\ell Z$	$3\ell Z$ veto	$2\mu SS$	$2\ell OSZ$ veto	$2\ell OSZ$
Z-mass selection	$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	$ m_{\ell\ell} - m_Z > 10 \text{ GeV}$	-	$ m_{\ell\ell} - m_Z > 10 \text{ GeV}$	$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$
Additional selection			$E_T^{\text{miss}} > 40 \text{ GeV}$ $H_T > 240 \text{ GeV}$	$E_T^{\text{miss}} > 40 \text{ GeV}_{(ee, \mu\mu)}$ $H_T > 130 \text{ GeV}_{(e\mu)}$ $\Delta R_{\text{ave}}^{ij} > 0.75$	$\Delta R_{\text{ave}}^{ij} > 0.75$
Lepton flavour	all trilepton	all trilepton	$\mu\mu$	all dilepton	$ee, \mu\mu$
Signal	$t\bar{t}Z$	$t\bar{t}W$ dominated	$t\bar{t}W$ dominated	$t\bar{t}Z$ and $t\bar{t}W$	$t\bar{t}Z$ dominated
Main background	tZ , WZ and fakes	$t\bar{t}Z$, $t\bar{t}H$ and fakes	$t\bar{t}Z$, $t\bar{t}H$ and fakes	$t\bar{t}$ +jets	Z +jets
Validation regions	$(3j + 2j + 1j, 1b)$ (CRZ)	$(1b)$ (CRW)	$E_T^{\text{miss}} < 40 \text{ GeV}$		
Regions in the fit (Signal region, control region)	$(\geq 4j, 1b)$ (SRB1J4) $(3j, \geq 2b)$ (SRB2J3) $(\geq 4j, \geq 2b)$ (SRB2J4)	$(3j + 2j, \geq 2b)$ (SRW3 ℓ)	$(\geq 2j, \geq 2b)$ (SR2 μSS)	$(3j, 1b + 2b)$ $(4j, 1b + 2b)$ $(\geq 5j, 1b + 2b)$	$(3j, 2b)$ $(4j, 2b)$ $(\geq 5j, 2b)$

SM (NLO) predictions: $\sigma(t\bar{t}Z) = 206 \pm 29 \text{ fb}$ and $\sigma(t\bar{t}W) = 203 \pm 25 \text{ fb}$

Measured : $\sigma(t\bar{t}Z) = 150_{-50}^{+55} \text{ (stat)} \pm 21 \text{ (syst) fb}$

$\sigma(t\bar{t}W) = 300_{-100}^{+120} \text{ (stat)} \pm_{40}^{+70} \text{ (syst) fb}$

For each, 3.1σ excess over the bkg-only hypothesis